

DESIGN AND SIMULATION OF PV-POWERED MOTOR-PUMP RECIRCULATING WATER SYSTEM IN RICE FIELD CRAB FARM USING MPPT-BASED NEURO-FUZZY AND BIDIRECTIONAL CONVERTER CHARGER CONTROLLERS

Rati Wongsathan^{1,*}, Isaravuth Seedadan¹ and Wutthichai Puangmanee²

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Abstract

Community enterprises engaged in rice field crab farming face significant challenges due to the absence of an electricity grid, resulting in energy shortages that hinder the operation of a 24-hour recirculating water system, essential for maintaining optimal conditions during the crab laviculture phase. Consequently, crab larva survival rates have experienced a significant 60% decline. To address this issue, this paper introduces the design and simulation of an off-grid photovoltaic solar-powered motor-driven water pumping system (PVWPS) using maximum power point tracking (MPPT) and charger controllers, to meet the power demands. The proposed MPPT-based neuro-fuzzy controller (NFC), in conjunction with a proportional-integral-derivative (PID) controller, maximizes the utilization of PV power for the motor pump. Additionally, a bidirectional converter facilitates battery charging and discharging. The motor speed, which directly influences the required pump flow rate, is regulated by controlling the voltage across the DC-linked capacitor, using an additional proportional-integral (PI) controller. The K_p , K_i , and K_d parameters of both the PID and PI controllers are meticulously adjusted through a genetic algorithm (GA) to optimize control performance. Simulation results demonstrate the effectiveness of the implemented MPPT-NFC and charge controller. The energy utilization efficiency can be increased by up to 97% and the overall efficiency of the PVWPS is improved by up to 10.5%, effectively overcoming the power shortage challenge. Consequently, the proposed PVWPS, utilizing MPPT-NFC with PID-controller and a bidirectional converter PI-controller, enables 24-hour operation of the recirculating water system, with the anticipation of an increased crab larva survival rate.

Keywords: PVWPS; Bidirectional converter; MPPT; Neuro-fuzzy controller (NFC); PID; Genetic algorithm (GA); Rice field crab farming

¹ Department of Electrical Engineering, Faculty of Engineering and Technology, North-Chiang Mai University, Hang Dong, Chiang Mai 50230, Thailand. E-mail: rati@northcm.ac.th; isaravuth@northcm.ac.th

² Department of Computer Engineering, Faculty of Engineering and Technology, North-Chiang Mai University, Hang Dong, Chiang Mai 50230, Thailand. E-mail: wutthichai@northcm.ac.th

* Corresponding author

Introduction

Rice field crabs, as depicted in Figure 1 (bottom-left), hold significant economic importance in Thai cuisine, known for their distinctive taste and aroma. In the past, these crabs were easily found in rice fields. However, changes in rice field ecosystems resulting from monoculture, chemical agriculture, and climate change have caused a notable decline in rice field crab populations. Despite these challenges, the demand for rice field crabs remains high, with an annual consumption of approximately 45 million individuals, as reported by Champeeratana *et al.* (2023).



Figure 1. Rice field crab farming worksite in Hankaew district, Hangdong, Chiang Mai, Thailand. (Top) PV module installations, (Bottom): (Left) Commercial MPPT charger in the control cabinet, (Middle) Existing recirculation water system, and (Right) Rice field crab and larvae (small black spots)

Generally, female crabs produce 500-700 offspring annually, with a growth period of 6-8 months and involving 13-15 molts. However, in rice field crab cultivation, young crabs are vulnerable to predation by other crabs during the molting process. This vulnerability leads to a reduction in the survival rate, typically around 60%. Therefore, a crab nursery is a crucial step in rice field crab farming, typically lasting for 1-2 months. To address the challenges associated with cannibalism during molting, the use of a segregated pond that provides adequate space to reduce aggressive crab interactions has been proposed. This system closely mimics the natural habitat of rice field crabs but requires an additional water recirculation system. By continuously filtering and treating the water, this system effectively removes waste products and maintains optimal oxygen levels, thereby mitigating the stress experienced by rice field crabs during molting.

However, rice field crab farms are often located in remote areas without access to the electricity grid. For example, the community enterprises in the Hankaew district of Hangdong, Chiang Mai province of Thailand serve as an area of study. To tackle this issue, solar photovoltaic (PV) generators are deployed. However, the operation of the recirculating water system requires continuous 24-hour operation, exceeding the capacity of the limited available batteries. Despite a significant cost investment of approximately 100,000 THB (3,000 USD) per recirculating pond, the existing PV system, shown in Figure 1 (top), fails to meet the required specifications due to improper design and control. Therefore, a well-designed solar PV-powered motor-driven water pump system (PVWPS), integrated with not shown in the references list. With power electronic converters, coupled with efficient controllers, is essential to enhance energy utilization efficiency and overcome the power shortage challenge.

In the literature, various topologies and components are used in PVWPS. In PV direct-coupled motor-pump applications, DC-DC converters, including the boost converter (Nabil *et al.*, 2020), buck converter, and buck-boost converter (Tawana *et al.*, 2021), are utilized to address the power mismatch between the PV generator and the motor-pump. These converters operate using the maximum power point tracking (MPPT) technique to ensure the maximum extraction of PV energy from the PV panels, even under changing weather conditions.

MPPT-based controllers within the PVWPS can be categorized into two groups: electrical input-based methods, including perturb-and-observe (P&O) (Tawana *et al.*, 2020, 2021), incremental conductance (INC) (Errouha *et al.*, 2020), model predictive control (MPC) (Massaq, 2023), and fuzzy logic control (FLC) (Tawana *et al.*, 2020; Belgacem *et al.*, 2022). There are also non-electrical input-based methods, including the neural network-based controller (NNC) (Tawana *et al.*, 2020; Massaq, 2023) and neuro-fuzzy controller (NFC) (Aljafari, 2022). Among these, FLC and NNC, both being artificial intelligence-based methods, are highly recommended for PVWPS (Muralidhar and Rajasekar, 2021).

FLC is considered a high-performing controller due to its ability to handle multiple command rules. However, the complexity that arises from designing these rules may lead to errors in achieving the maximum power point (MPP). In contrast, NNC, with its single control rule and step-size-free approach, achieves the MPP through a training and learning process.

To improve energy reliability, maintaining a continuous and consistent power supply in PVWPS with batteries, bidirectional converters assume a crucial role (Iskak *et al.*, 2019). Rechargeable batteries, when connected with a bidirectional converter, provide instant power delivery to compensate for voltage fluctuations during the boost mode operation. Additionally, they store excess PV energy generated during periods of high sunlight for later usage during nighttime or cloudy periods in the buck mode operation. However, several factors, including battery capacity and the necessity to balance power demand from the load with the available energy from the PV panel and the battery, must be considered.

In this study, a small-scale PVWPS prototype is designed and implemented using MATLAB software for the recirculating water system in rice field crab farming, aiming to validate the performance outcomes before installing the actual devices. The system integrates a boost converter with an MPPT controller and a bidirectional converter with a voltage regulator to achieve the desired motor speed and pump flow rate, while also making use of lithium-ion batteries. The primary objective is to ensure continuous 24-hour operation, thereby improving crab larvae survival rates, while maintaining cost considerations.

To achieve this goal, a DC motor-pump with a power rating of less than 1 kW, readily available in the local appliance shop, was chosen as a practical alternative to an AC motor. The latter would require a solar pump inverter, resulting in higher costs and a more complex control system (Nisha and Gnana Sheela, 2020). The selected system incorporates a commonly used centrifugal pump driven by a permanent magnet DC (PMDC) motor, which provides a constant speed to the pump shaft, aligning effectively with the tracked maximum power points (MPPs) (Wongsathan, 2020).

To optimize the extraction of the MPP, an efficient MPPT controller is employed, in conjunction with a PID controller through the boost converter. An alternative approach to improving MPPT is the use of NFC, which combines the capabilities of self-generated fuzzy rules of FLC with adaptive learning of NNC to fine-tune the system parameters, offering a hybrid approach.

Lithium-ion batteries instead of lead-acid batteries are chosen to store the energy for operation during the night and cloudy conditions during the day due to the advantage of fast charge. A PI controller, serving the battery charger, regulates the voltage at the DC-linked capacitor by controlling the bidirectional converter, ensuring effective battery charging-discharging to meet the motor-pump power requirements and maintain system

stability. Despite the simplicity and ease of implementation of PID and PI controllers, the selection of their parameters, including K_p , K_i , and K_d , is limited by the nonlinear nature of the PVWPS. In modern control optimization, instead of relying on trial-and-error tuning by humans, these parameters are adjusted using population-based search algorithms such as Artificial Bee Colony (ABC), Genetic Algorithm (GA) (González *et al.*, 2021), and Particle Swarm Optimization (PSO) (Zhang *et al.*, 2022). To enhance the control performance of the PID and PI controllers, in this work, GA is chosen to fine-tune these parameters offline, as it is well-suited for exploring the large search space associated with these parameters.

Proposed Methods

The PVWPS description

The overall PVWPS depicted in Figure 2 comprises five electrical components: a PV generator, a DC-DC boost converter, a bidirectional converter, a rechargeable battery (Lithium-ion battery), and a PMDC motor coupled with a centrifugal pump as the load. It also includes two segments of controllers: an MPPT-NFC with a PID controller in the boost converter stage, and an additional PI controller for voltage regulation in the bidirectional converter stage.

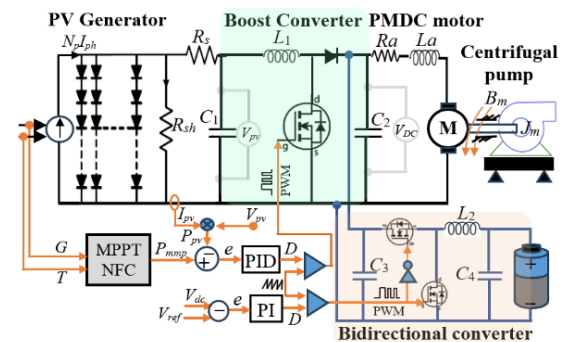


Figure 2. Schematic diagram of the off-grid PV-powered motor-driven water pump system (PVWPS) with controllers

The PV panel, serving as the current generator source, is connected to the boost converter to increase the PV voltage to match the reference voltage (V_{ref}) across the DC-linked capacitor. To transfer the maximum available PV power to the load, the MPPT-NFC tracks the MPPs under the conditions of solar irradiance (G) and ambient temperature (T). The errors between the measured PV power (P_{PV}) and the estimated MPP serve as

inputs for the PID control, which generates the duty ratio (D) that is converted to the pulse width modulation (PWM) signal used to switch the boost converter. The bidirectional converter operates in two main modes based on the P_{PV} : in buck mode, when the P_{PV} is greater than the required load power, the excess power is transferred to charge the battery, and in boost mode, when the P_{PV} is less than the required load power, the battery power, together with the P_{PV} , are supplied to the load. Therefore, the battery should be fully charged during the day to supply power to the load at night and provide backup in cloudy conditions. To control the motor speed, including maintaining the constant flow rate of the pump, the varying voltage across the DC-linked capacitor (V_{DC}) is regulated to meet V_{ref} using the PI controller.

The PVWPS design

Sizing a PVWPS under variable motor speed based on water demand, sunlight availability, and system load is a challenging task due to the complexity in accurately estimating power requirement, optimizing system efficiency, and achieving MPPT. By assuming that the characteristics of the pump and motor are known for a fixed speed, the performance of PVWPS can be analyzed at the steady state.

In PVWPS design, the recirculation pond with dimensions of $0.8 \times 15 \times 0.15 \text{ m}^3$ in the rice field crab nursery requires an approximate volumetric flow rate (q) of $7 \text{ m}^3/\text{hr}$. Using Equation (1) with a low total pump head (TPH) of 5 m, the hydraulic power (P_h) is calculated to be approximately 97 W. Considering a pump efficiency (η_{pump}) and motor efficiency (η_{motor}) within the range of 60% to 90% (here, we use 60% in the simulation), Equation (1) estimates the power of the motor (P_m) driving the pump to be around 270 W. As a result, a motor with a rated power of 300 W (or 2/5 HP), a nominal voltage of 36 V (input voltage range 12–56 V), and a rated current of 15 A, with a maximum speed of 1,725 RPM (revolutions per minute), is selected, along with a required DC voltage (V_{DC}) supply to the motor of 60 V.

$$P_m = \frac{P_h}{\eta_{pump} \times \eta_{motor}} = \frac{q \times \rho \times g \times TPH}{(3.6 \times 10^3) \times \eta_{pump} \times \eta_{motor}} \quad (1)$$

Here, g represents gravitational acceleration (9.8 m/s^2) and ρ is water density ($1,000 \text{ kg/m}^3$).

To ensure nighttime backup power from 6 pm to 6 am and provide a 2-hour reserve for daytime cloudiness when the PV power (P_{PV}) falls below the

preferred threshold (P_{ref}), a battery is incorporated into the system. The battery is relatively expensive due to its capacity. Our choice preferred a lithium-ion battery over a lead-acid battery due to the advantage of fast charging (see comparison in Figure 3). Two lithium-ion batteries connected in parallel, each with a rated battery voltage (V_{bat}) of 36 V and capacity (C_{rated}) of 130 Ah or 9,360 Wh, ensure adequate power requirements. To prolong the battery life and health during daily operation, the terminated discharge level should be 50% of SoC. Testing with the selected motor (Figure 3), the lithium-ion battery can supply up to 15 hours and requires about 6 hours for near full charge, compared to the lead-acid battery, which requires over 12 hours.

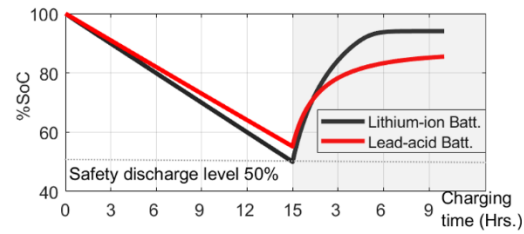


Figure 3. SoC against the required time for charging-discharging the battery

During PMDC motor operation, back electromotive force (EMF, E_b) depends on the supply voltage (V_{DC}) and angular velocity (ω) of the shaft, expressed as $E_b = K_e \times \omega(t)$, while the torque (τ) turning the motor attached pump is developed by current through armature inductance (L_a), where K_e denotes back EMF constant. The differential equations for the equivalent PMDC motor circuit (Figure 2) used in the simulation can be expressed in both transient and steady-state conditions (i.e., $dI_a/dt = 0$ and $d\omega/dt = 0$) as follows,

$$\frac{dI_a(t)}{dt} = \frac{V_{DC}(t)}{L_a} - \frac{R_a}{L_a} I_a(t) - \frac{K_e}{L_a} \omega(t); \quad V_{DC} = R_a I_a + K_e \omega \quad (2)$$

$$\frac{d\omega(t)}{dt} = \frac{\tau_{motor}}{J_m} - \frac{B_m}{J_m} \omega(t) - \frac{\tau_{pump}}{J_m}; \quad \tau_{motor} = B_m \omega + \tau_{pump} \quad (3)$$

where I_a and R_a are the armature current and resistance respectively, J_m is rotor inertia, B_m is viscous friction coefficient, τ_{motor} is motor torque, and τ_{pump} is pump torque.

In simulation under steady-state conditions, a selected 300 W PMDC motor has a specification of N_{max} of 1,725 RPM or ω_{max} of 181 rad/sec, and

a required speed (N) of 1,200 RPM or ω of 125 rad/sec. At the no-load condition ($\omega = \omega_{max}$): $V_{DC} = E_b = 60$ V, and the value of $K_e = E_b/\omega = 0.331$ V/rad/sec. At a locked rotor condition (i.e., $\omega = 0$ or $E_b = 0$), considering the given stall current of 21.5 A (i.e., maximum current drawn by the motor), so $R_a = V_{DC}/21.5$ or 2.8Ω . At the required operation speed, $E_b = 41.4$ V and $I_a = 7$ A. Other setting values include $L_a = 5$ mH, $J_m = 0.0023$ kg·m², and $B_m = 0.0015$ N·m/rad/sec. Here, $\tau_{motor} = K_t \times I_a(t)$, where K_t equals K_e . To calculate the driving torque of the centrifugal pump, Equation (4) (Sontake *et al.*, 2020) is utilized. The mechanical power developed by the motor can be expressed as,

$$P_m = \tau_{pump} \times \omega \\ = (A_{pump} + K_{pump} \omega^L) \times \omega \quad (4)$$

where assuming that A_{pump} represents zero load friction and considering the pump constant denoted by L as 1.8. In addition, for a selected P_m of 300 W and a desired motor speed of 125 rad/sec, the value of K_{pump} in Equation (4) is approximately 4×10^{-4} .

Based on the above requirements, a PV polycrystalline module of 17% efficiency (η_{PV}) with the following specifications at standard test conditions (STC) of $G = 1,000$ W/m² and $T = 25^\circ\text{C}$ is selected: a rated power of 250 W, a voltage at the MPP of 31 V, a current at the MPP of 8.5 A, an open-circuit voltage of 38 V, and a short-circuit current of 9 A. To meet the power demands for both supplying the motor-pump and simultaneously charging the battery, the converter power ($V_{DC} \times I_a$) needs to be 420 W. During sunlight, more than twice this power is required for charging the battery for nighttime and cloudy conditions during the day. Therefore, at least four PV modules are required.

Figure 4 illustrates the characteristics of the PV array with four modules connected in parallel, showing the PV current-voltage (I_{PV} - V_{PV}) and power-voltage (P_{PV} - V_{PV}) under two scenarios: varying G with a constant T of 25°C and varying T with a constant G of $1,000$ W/m². At the STC, the PV array has a rated power (P_{rated}) of 1 kW, with a voltage at the MPP (V_{MPP}) of 31 V and a current at the MPP (I_{MPP}) of 35 A. It is evident that an increase in T from 25°C to 45°C has a relative impact on the reduction of available PV power for supplying the motor-pump. However, under specific conditions of G , specifically when G is less than 400 W/m², the generated PV power is insufficient, falling below the required 300 W for the motor. In such cases, additional power is drawn from the battery. Conversely, when G exceeds 400 W/m², typically occurring between 8:30 am and 4:00 pm (approximately 7 hours of charging), the average

excess PV power $(1000-420) \times 7 = 4$ kWh is utilized to charge the battery, ensuring an adequate supply for the motor-pump for up to 12 hours ($9,360 \times 0.43 = 0.4$ kWh, as depicted in Figure 4).

In order to design the boost converter under STC, the input voltage (V_{in}) is set to 31 V (or V_{MPP}), and the desired output voltage (V_{out}) or V_{DC} is referenced at 60 V (or V_{ref}). The corresponding output current (I_{out}) can be calculated as P_{rated}/V_{out} , resulting in 17 A. The inductance (L_1) and capacitance (C_1 and C_2) can be determined as follows (Iskak *et al.*, 2019),

$$L_1 = \frac{V_{in} \times (V_{out} - V_{in})}{\Delta I_L \times f_s \times V_{out}} \quad (5)$$

and

$$C_1 = C_2 = \frac{I_{out} \times (V_{out} - V_{in})}{\Delta V_o \times f_s \times V_{out}} \quad (6)$$

respectively, where ΔI_L represents the inductor current ripple, ΔV_o represents the output voltage ripple, and f_s denotes the switching frequency.

For f_s of 10 kHz, with a desired ΔI_L and ΔV_o of 5%, L_1 can be calculated to be 0.9 mH, and C_1 and C_2 are determined to be 270 μF . To design the bidirectional converter with the same parameters, except for setting the input voltage (V_{in}) to 36 V (or V_{bat}), L_2 is calculated as 1 mH. Moreover, C_3 and C_4 are determined to be 226 μF .

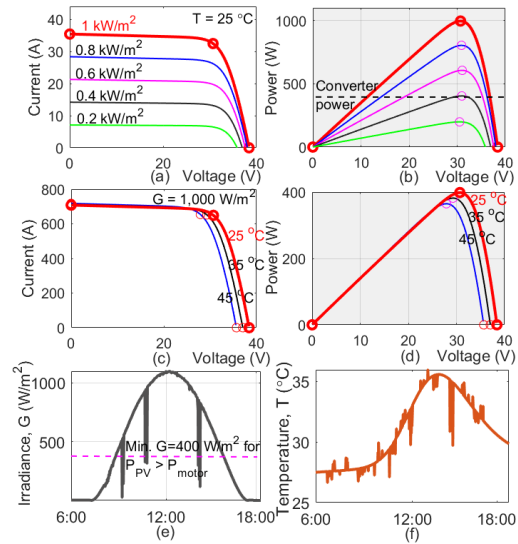


Figure 4. PV current-voltage (a) and (c) along with PV power-voltage (b) and (d) characteristics under constant T and constant G , and (e) solar irradiance (G) and (f) ambient temperature profiles throughout the day

The MPPT-based NFC design

The MPPT-NFC (Figure 5(a)) incorporates five layers: input layer, fuzzification layer, rule layer, defuzzification layer, and output layer. In the input layer, two neurons represent the normalized inputs of G and T ranging between 0 and 1. The fuzzification layer maps these crisp inputs to fuzzy strengths (μ) using Gaussian membership function associated with linguistic terms, such as NB (negative big), NS (negative small), Z (zero), PS (positive small), and PB (positive big). Consequently, the output of this layer produces $\mu_{G,NB}, \mu_{G,NS}, \dots, \mu_{G,PB}$ for the crisp value of G , and $\mu_{T,NB}, \mu_{T,NS}, \dots, \mu_{T,PB}$ for the crisp value of T . In the rule layer, each node represents a fuzzy rule that connects the fuzzy sets $G = \{NB, NS, Z, PS, PB\}$ and $T = \{NB, NS, Z, PS, PB\}$ to the output variables mmp . Thus, a total of 25 self-generated fuzzy rules exist. In a first-order Sugeno neurofuzzy model, the consequent part of each rule is represented by a linear function of the input variables G and T , for instance:

Rule (1): If G is NB and T is NB , THEN $mmp_1(G, T) = P_1 \times G + Q_1 \times T + R_1$,

Rule (25): If G is PB and T is PB , THEN $mmp_{25}(G, T) = P_{25} \times G + Q_{25} \times T + R_{25}$.

Here, P_i , Q_i , and R_i represent the parameters of the linear outputs. To evaluate the rule antecedent, the product for T -norm (logical AND) is selected, resulting in weight value by,

$$w_i = \mu_{G,x}(G) \times \mu_{T,y}(T), \quad i = 1, 2, \dots, 25, x \in G, y \in T. \quad (7)$$

In the defuzzification layer, each neuron generates a fuzzy output (mpp_i) corresponding to the weighted values (w_i). Finally, in the output layer, all the fuzzy outputs defuzzified from the previous layer are converted into a crisp value (P_{MMP}) using the weighted average method.

$$P_{MMP} = \frac{\sum_{i=1}^{25} w_i \times mpp_i(G, T)}{\sum_{i=1}^{25} w_i} \quad (8)$$

The data acquisition system collects the data required for training the NFC, which includes input variables of G and T , and output variables of V_{PV} , I_{PV} , and P_{MMP} . This system incorporates various sensors, including irradiance, temperature, and current and voltage sensors. These measurements are utilized to estimate the MPP, which is crucial for optimizing the MPPT performance.

The PID and PI controllers are designed using GA

The PID controller plays a crucial role in regulating the PV power to minimize errors and ensure optimal MPPT performance. The output of the PID controller in the MPPT is the duty ratio (D) of the boost converter, which determines the switching time of the power electronic devices. The duty ratio is calculated based on the errors (e) between the estimated and measured PV power, as well as the three parameters of the PID controller: K_p (proportional gain), K_i (integral gain), and K_d (derivative gain), which can be expressed as follows:

$$D = K_p \times e + K_i \times \int edt + K_d \times \frac{de}{dt}. \quad (9)$$

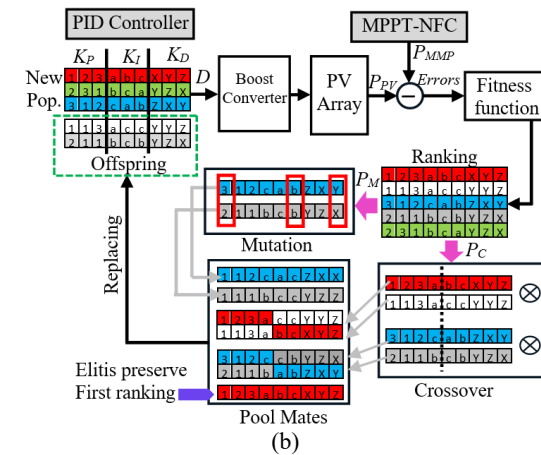
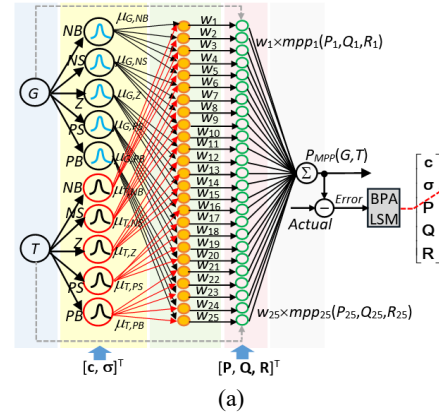


Figure 5. Schematic diagram of the controller design for the PVWPS (a) MPPT-based NFC and (b) GA optimization for PID and PI controllers

By adjusting the values of K_p , K_i , and K_d , the PID controller can effectively regulate D to minimize errors and maintain optimal power transfer in the system. Figure 5(b) illustrates the tuning and optimization of these parameters accurately using a GA. The process begins by initializing a population of potential solutions called chromosomes, where each solution represents a set of PID parameter values. After determining D using an individual chromosome (Equation (9)) and applying the generated PWM signal to the boost converter, the errors for predefined sampling time are summed to assign rankings to all chromosomes based on their strength through a fitness function in Equation (10). The fitness function incorporates weighted combinations of transient and steady-state errors to consider the best chromosome.

The best one is preserved using an elitism strategy to ensure their survival to the next generation, while the rest are selected using the roulette wheel method by assigning a high probability of selection to the fittest individuals. For the reproduction process, during crossover, two parent chromosomes are combined with the crossover rate P_C to create offspring solutions that inherit traits from both parents. Mutation introduces random changes in the individual chromosomes with the mutation rate P_m , ensuring diversity in the population. It is generally suggested to have a high P_C and a low P_M for the convergence of the solution. Here, P_C and P_M are selected as 0.9 and 0.15, respectively. The offspring and preserved chromosomes are combined in the mating pool to replace the previous generation's population. This cycle of evaluation, selection, crossover, mutation, and replacement continues until the GA converges to a solution with PID parameters that yield the best

performance, effectively minimizing the errors between the estimated and measured PV power. The fitness function (Equation (10)) is used to evaluate the i^{th} chromosome, with K_1 and K_2 representing weighted integer constants.

$$f_i = (K_1 \sum_{k=1}^{K_1 T} |err(k)| + (K_2 - K_1) \sum_{k=K_1 T+1}^{K_2 T} |err(k)|)^{-1} \quad (10)$$

Once the optimization process is completed, the optimized set of PID parameters is obtained. In the case of the PI controller for regulating the DC-linked voltage, K_p and K_i are adjusted through the GA similar to the PID controller.

Results and Discussion

The specification and design values of the electrical components of the PVWPS, including the controller parameters, are summarized in Table 1. These parameters are used in the simulation, as shown in the circuit diagram implemented in MATLAB/Simulink (Figure 6).

The control results for four different conditions of G at 1000, 800, 600 and 100 W/m², with a constant temperature of $T = 25^\circ\text{C}$, are depicted in Figure 7. Figure 7(a) presents the estimated MPPs (represented by the blue line) obtained from the proposed MPPT-NFC with PID controller compared with the exact MPPs indicated in parentheses: 997 W (1000 W), 793 W (803 W), 610 W (616 W), and 89 W (97 W). The energy utilization efficiency (η_{MPPT}), calculated as the average summation of the obtained MPP divided by the exact MPP, is approximately 97.3%.

Table 1. Parameters and their designed values used in the PVWPS with controllers

Parameter	Value	Parameter	Value
Flow rate (q)	7 m ³ /hr	Rotor inertia (J_m)	0.0023
Total pump head (TPH)	5 m	Viscous friction coefficient (B_m)	0.0015
Hydraulic power (P_h)	97 W	Pump coefficient (L)	1.8
Pump efficiency (η_{pump})	60%	Pump constant (K_{pump})	4×10^{-4}
Motor efficiency (η_{motor})	60%	Rated PV power (P_{rated})	1 kW
PV efficiency (η_{PV})	17%	PV voltage at MPP (V_{MPP})	31 V
Motor power (P_m)	300 W	PV current at MPP (I_{MPP})	35 A
Motor speed (N_{max})	1725 RPM	Boost inductance (L_1)	0.9 mH
Motor speed (ω_{max})	181 rad/sec	Boost capacitance (C_1, C_2)	270 μF
Battery voltage (V_{bat})	36 V	Bidirectional inductance (L_2)	1 mH
Battery capacity (C_{rated})	130 Ah	Bidirectional capacitance (C_3, C_4)	226 μF
Battery power rated (P_{rated})	9,360 Wh	Proportional constant (K_p) (PID)	0.00535
DC-linked voltage ($V_{\text{DC}}=V_{\text{ref}}$)	60 V	Integral constant (K_i) (PID)	0.52547
Motor torque constant ($K_t=K_i$)	0.33 V/rad/sec	Derivative constant (K_d) (PID)	0.00031
Resistance armature (R_a)	2.8 Ω	Proportional constant (K_p) (PI)	0.00023
Inductance armature (L_a)	5 mH	Integral constant (K_i) (PI)	0.03213

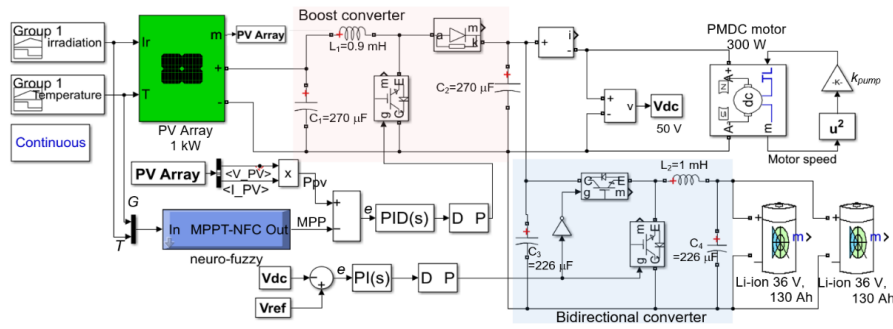


Figure 6. Circuit diagram of the PVWPS with the implementation of the proposed controllers using MATLAB/Simulink software

For the first three conditions, it is observed that the PV power (997, 793, and 610 W) exceeds the motor power (300 W), resulting in excess energy of 200 W, which is used to charge the battery (indicated by the negative power value in the black line). In contrast, in the last condition, the PV power (89 W) is lower than the motor power (300 W), leading to the supplementation of power drawn from the battery (411 W) indicated by the positive power value in the black line. The converter power and motor power stabilize at 500 W and 300 W, respectively. The PV voltage is regulated at the V_{MPP} with a value of 30.7 V (indicated by the blue line in Figure 7(b)), while the output of the boost converter maintains a desired level of 60 V (indicated by the red line in Figure 7(b)). The motor operates at a constant speed of 1,070 RPM (Figure 7(c)), and the armature current is about 8 A (Figure 7(d)). Consequently, the motor loss, determined by $I_a^2 \times R_a$, amounts to about 179 W, resulting in a motor efficiency of 0.62%, which closely aligns with the simulation value of 60% used in Equation (2)). The motor torque in Figure 7(d) measures approximately 3 Nm, which is suitable for a motor of small power.

Typically, the overall efficiency of a PVWPS, considering the combined efficiencies of all components, falls within the range of 10% to 30%. This range accounts for losses in the PV module, motor, pump, power electronics, and other system components. In our design and simulation, taking into consideration the output parameters, the calculated overall efficiency of the PVWPS, determined by $\eta_{PV} \times \eta_{MPPT} \times \eta_{conv} \times \eta_{motor} \times \eta_{pump}$, is $0.17 \times 0.97 \times 1.0 \times 0.62 \times 0.6$, resulting in an overall efficiency of 10.5%. Here, we assume the converter to be ideal.

To enhance the PVWPS efficiency, consider switching to high-efficiency monocrystalline PV modules (17%-22%). Also, opt for more efficient motors, pumps, and advanced control techniques for improved overall efficiency.

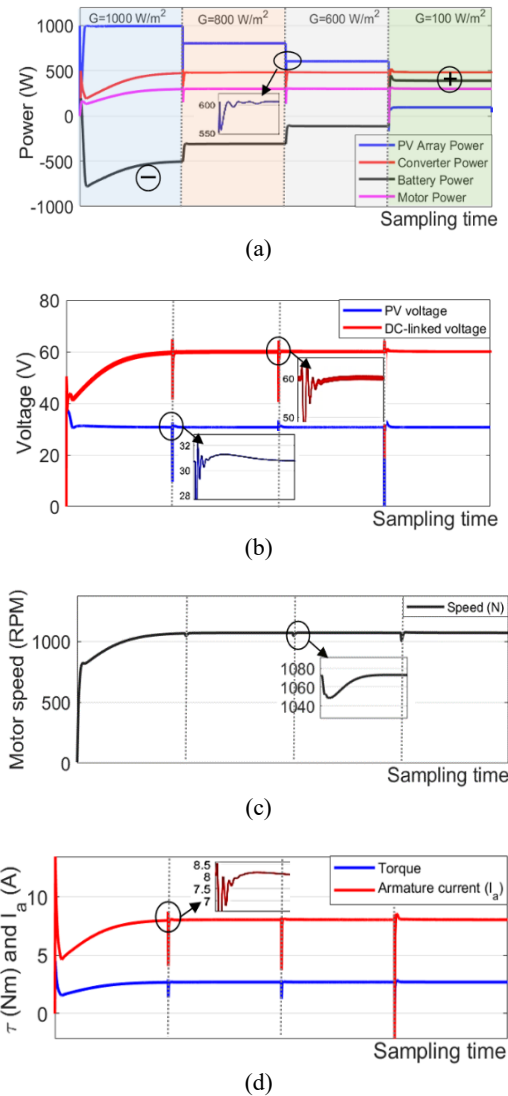


Figure 7. Schematic diagram of the controller design for the PVWPS (a) MPPT-based NFC and (b) GA optimization for PID and PI controllers

By incorporating motors and pumps with efficiencies of around 90%, the overall efficiency of the system can increase up to 17%.

However, it is important to consider the cost implications associated with these efficiency-enhancing measures. Moreover, there is a need to improve the control performance during transient while exhibiting fluctuations (as can be seen in the expanded figures in Figure 7). These fluctuations can lead to electronic stress and heating, thereby degrading the overall performance of the system.

Furthermore, the performance of the proposed PVWPS with the controller in terms of MPPT and charger operation is validated during daytime operation. The simulation results, depicted in Figure 8, clearly illustrates the successful collaboration between the generated PV power and the stored battery power in supplying the power demands of the motor-pump, even under cloudy conditions.

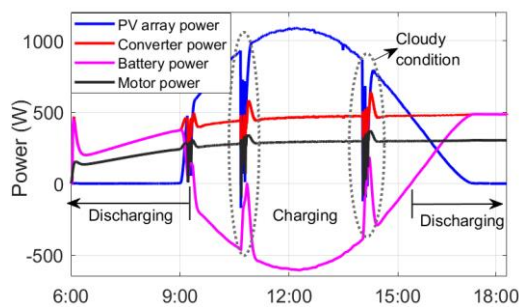


Figure 8. Generated PV and stored battery power for motor-pump operation during daytime under cloudy conditions

Conclusions

By implementing a comprehensive design and control strategy that integrates power electronic converters and incorporates lithium-ion battery storage, an efficient and reliable PVWPS with controllers has been designed and implemented, achieving satisfactory overall efficiency. This system is specifically designed for use in a 24-hour recirculating water system within rice field crab farming, with the primary objective of increasing the survival rate of rice field crab larvae. To achieve this objective, the utilization of an efficient MPPT-NFC technique with a PID controller through a boost converter, along with a bidirectional converter functioning as a charger with a PI controller through a bidirectional converter, holds great significance. The parameters of both PI and PID controllers have

been systematically optimized using a GA to ensure the controller's effectiveness in achieving the desired control results. In practical implementation, the proposed controller can be effectively realized through the cost-effective Arduino Uno board microcontroller. Future work will focus on the hardware implementation and installation of the PVWPS along with the associated controllers, transitioning the design from a conceptual framework to a real-world application.

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